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Closing an open system: Pore pressure changes in permeable edifice rock at high strain rates

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ABSTRACT

A permeable or open system will react as a closed system if the rocks implicated are deformed on a timescale that precludes fluid movement. Closed system ("undrained") deformation therefore leads to a failure mode dependent change in pore pressure: microcracking (dilatant behaviour) and cataclastic pore collapse (compactant behaviour) will decrease and increase pore pressure, respectively. In the dilatant regime (i.e., in the shallow edifice, <1 km depth), a decrease in pore pressure will serve to strengthen rock—a process termed dilatancy hardening. However, it is shown here, using undrained triaxial deformation experiments, that the high initial porosity and microcrack density of typical edifice-forming andesites prevent dilatancy hardening. This allows the rock proximal to the magma-filled conduit in the shallow edifice to remain weak during periods of unrest when high magma strain rates could be transferred to the adjacent country rock. Although the propensity for fracturing will likely reduce the structural integrity of the edifice, fracturing of the shallow edifice may improve the outgassing efficiency of the nearby magma-filled conduit. The increase in pore pressure during undrained deformation in the compactant regime (i.e., in the deep edifice, >1 km depth) could lead to pore pressure embrittlement and fracturing. Indeed, the experiments of this study show that the pore pressure increases during progressive compaction in a closed system. However, the pore pressure is prevented from reaching the critical value required to promote a dilatant response (i.e., fracturing) for two reasons. First, the rate of compaction (i.e., porosity decrease) slows as the sample is deformed at a constant strain rate, a consequence of the decay in effective pressure. Second, the emergence of microcracking as the rock approaches the compactant–dilatant transition acts as a negative feedback and prevents the rock from transiting into the dilatant field. At this point, local porosity increases due to dilatant microcracking and local porosity decreases due to cataclastic pore collapse are balanced and the rock deforms without further changes to porosity or pore pressure. This will prevent potentially destabilising brittle failure deeper in the edifice during the high strain rates that may accompany unrest and, although it precludes the formation of efficient outgassing pathways in the form of fractures, undrained deformation in the compactant regime will prevent a reduction in porosity and permeability and may therefore facilitate lateral outgassing of the conduit into the country rock. We assess the conditions (strain rate and permeability) required for drained or undrained deformation by defining a dimensionless Darcy number. Closed system or undrained deformation is likely commonplace within a volcano (strain rates in the rock adjacent to an active volcanic system can be high and textural heterogeneities can serve as barriers to fluid flow) and therefore forms an important component for a complete understanding of the mechanical response of an edifice to the stress perturbations accompanying unrest.

1. Introduction

The rocks forming a volcanic edifice are subject to the stress perturbations that accompany volcanic unrest (e.g., Roman et al., 2004; Gerst and Savage, 2004). If the deformation of the edifice rock occurs on a timescale that precludes fluid movement—a function of the deformation rate and the permeability of the rock—the pore pressure inside edifice-forming rock will either increase or decrease in response to an imposed stress. Deformation in the dilatant regime (the prevalent failure mode anticipated in the shallow edifice, <1 km; Heap et al., 2015a) will result in an increase in porosity (dilation; e.g., Brace et al., 1966; Read et al., 1995) and therefore, in the absence of fluid movement, a decrease in pore pressure. By contrast, compactant deformation (the prevalent failure mode anticipated in the deep edifice, >1 km; Heap et al., 2015a) will result in a decrease in porosity (compaction; e.g., Wong and Baud, 2012) and therefore an increase in pore pressure is expected in the absence of fluid migration.

For volcanic rock, the failure mode (dilatant or compactant) depends on the physical attributes of the rock (porosity and pore diameter,

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amongst others) and the prevalent pressure conditions, i.e. the effective pressure ($P_{eff} = P_c - P_p$, where the effective pressure P_{eff} is assumed to be equal to the confining pressure P_c minus the pore fluid pressure P_p) (e.g., Heap et al., 2015a). In a scenario where the pore pressure can remain constant during deformation, high porosity volcanic rock (>0.1–0.15) will be dilatant in the shallow edifice (<1 km depth; i.e., low effective pressures) and compactant at depth (>1 km depth; i.e., high effective pressures) whilst low porosity volcanic rock (<0.1–0.15) will be dilatant at both low and high effective pressures (e.g., Kennedy et al., 2009; Zhu et al., 2011; Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a, 2015b). In the dilatant field, deformation is manifested as localised axial splits or shear fractures (e.g., Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a). Deformation in the compactive regime is characterised by either distributed cataclastic pore collapse (e.g., Zhu et al., 2011; Heap et al., 2015b) or the formation of localised bands of compacted pores (e.g., Loaiza et al., 2012; Adelinet et al., 2013; Heap et al., 2015a; Farquharson et al., 2016a).

In the dilatant field, an increase in the effective pressure (simplified here to be equivalent to an increase in depth in the edifice) increases the strength of rock (e.g., Paterson and Wong, 2005). Therefore, if the pore fluid pressure decreases due to dilatant deformation in a system that precludes fluid movement, the effective pressure will increase and the rock will strengthen. This phenomenon is called dilatancy hardening (e.g., Brace and Martin, 1968; Rice, 1975; Ismail and Murrell, 1976; Lockner and Stanchits, 2002; Paterson and Wong, 2005 and references therein). During deformation in the compactant field, in the absence of fluid movement, the increase in pore pressure as a result of compaction could reduce the effective pressure sufficiently to promote a dilatant response (i.e., fracturing)—a process termed pore pressure embrittlement (e.g., Farquharson et al., 2016a). In rock mechanics, the switch from a compactant to a dilatant failure mode is termed $C^{*\prime}$ (e.g., Schock et al., 1973; Baud et al., 2000, 2006; Heap et al., 2015a) and has previously been achieved through porosity loss and strain hardening in triaxial experiments in which the pore pressure is maintained at a constant value.

This study investigates: (1) dilatancy hardening in the dilatant regime and, (2) the potential for a switch in failure mode in the compactant regime in typical edifice-forming andesites (from Volcán de Colima, Mexico). To achieve these aims, triaxial experiments were performed in which water-saturated samples were deformed in a configuration in which water cannot enter or leave the sample (termed “undrained experiments” in studies of rock deformation; more information on undrained experiments is provided in the Materials and methods section). A scenario is envisaged in which saturated edifice host rocks experience a differential stress (e.g., the stress perturbations associated with magma ascent in the nearby magma-filled conduit) in a system that precludes drainage (deformation proceeds at a timescale that precludes fluid movement). The degree to which typical edifice rocks are water-saturated is therefore of particular interest to this study. The position of the water table beneath a stratovolcano can vary, and is a function of the rate of recharge, the heat input rate, and the hydraulic parameters of the system (Hurwitz et al., 2003). Although the water table at stratovolcanoes can be relatively deep (Hurwitz et al., 2003), perched water bodies, sandwiched between low-permeability layers, are also commonly observed or inferred at stratovolcanoes (e.g., Hurwitz et al., 2003; Finn et al., 2007).

In the scenario described above, dilatancy hardening could strengthen the edifice-forming rocks thereby increasing their resistance to fracture and promoting seismic quiescence (Scholz et al., 1973). A switch from a compactant to a dilatant failure mode in porous edifice rocks at depth could promote fracturing and provide new pathways for the lateral outgassing of the volcanic conduit in the adjacent country rocks (e.g., Jaupart, 1998; Collinson and Neuberg, 2012), or up through a fractured halo-zone that envelops the conduit (e.g., Rust et al., 2004; Lavallée et al., 2013; Gaunt et al., 2014; Plail et al., 2014; Young and Gottsmann, 2015). The ease with which exsolved gases can escape the conduit can impact the style and intensity of an eruption. Generally speaking, efficient outgassing promotes effusive behaviour and inefficient outgassing promotes explosive behaviour (as discussed by many authors, e.g. Eichelberger et al., 1986; Woods and Koyaguchi, 1994). Deep fracturing, as a result of pore pressure embrittlement, could also reduce the structural stability of the edifice and increase the risk of flank collapse (e.g., Voight, 2000).

2. Materials and methods

For the purpose of this study, two edifice-forming andesites from Volcán de Colima (Mexico) were selected. Although the materials are sourced from Volcán de Colima, the concepts presented in this study will be applicable to many active and frequently-collapsing andesitic stratovolcanoes, such as Ruapehu (New Zealand), Soufrière Hills volcano (Montserrat), Merapi (Indonesia), Santa María (Guatemala), and Tungurahua (Ecuador). The first block, C8, was taken from the 1998–1999 block-and-ash flow in the San Antonio ravine and contains a connected porosity of about 0.165. The second, B5, is from an older lava of unknown age and contains a connected porosity of about 0.075. The locations of the collection sites are indicated in Heap et al. (2014a; 2015a). Both andesites have a porphyritic texture consisting of a glassy groundmass containing abundant microlites and pores (59–68 vol.%) and a (commonly microcracked) phenocryst cargo (<1.5 mm in diameter) of plagioclase (13–25 vol.%), clinopyroxene (3–4 vol.%), and orthopyroxene (2–4 vol.%). The crystal fraction does

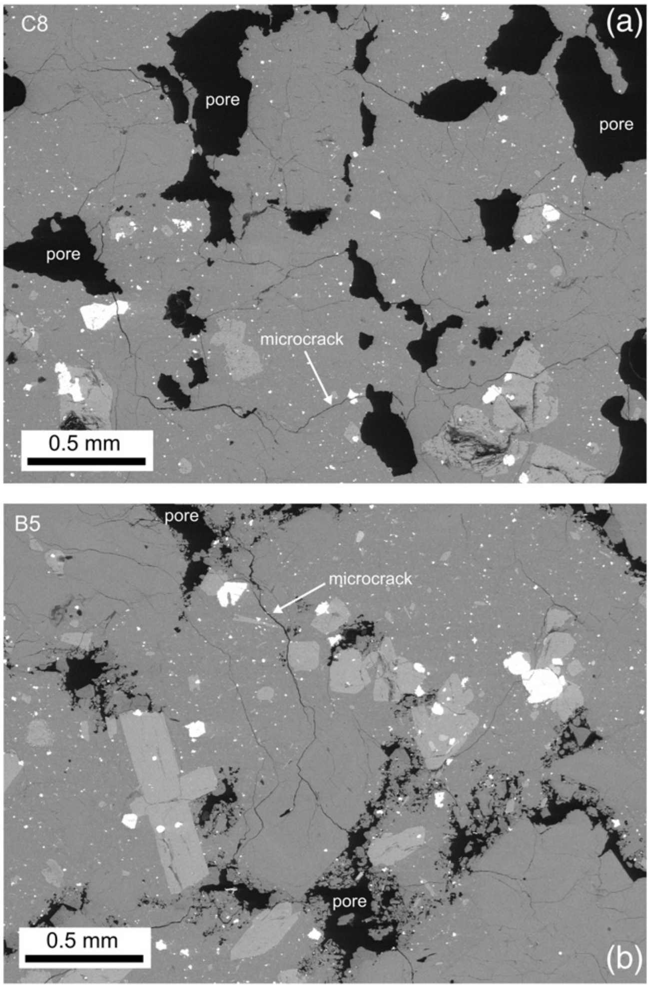

Fig. 1. The microstructure of the studied andesites from Volcán de Colima. (a) Back-scatted scanning electron microscope image of C8. (b) Back-scatted scanning electron microscope image of B5. The microstructural elements are highlighted on the pictures.